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Slow light enhanced gas sensing in photonic crystals

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ABSTRACT

Infrared spectroscopy allows for highly selective and highly sensitive detection of gas species and concentrations. Conventional gas spectrometers are generally large and unsuitable for on-chip applications. Long absorption path lengths are usually required and impose a challenge for miniaturization. In this work, a gas spectrometer is developed consisting of a microtube photonic crystal structure. This structure of millimetric form factors minimizes the required absorption path length due to slow light effects. The microtube photonic crystal allows for strong transmission in the mid-infrared and, due to its large void space fraction, a strong interaction between light and gas molecules. As a result, enhanced absorption of light increases the gas sensitivity of the device. Slow light enhanced gas absorption by a factor of 5.8 in is experimentally demonstrated at 5400 nm. We anticipate small form factor gas sensors on silicon to be a starting point for on-chip gas sensing architectures.

1. Introduction

Gas molecules exhibit discrete absorption lines caused by molecular vibrations at discrete energies [1]. These absorption lines are generally located in the mid- and near-infrared (MIR and NIR) range of the electromagnetic spectrum and form specific fingerprints of each gas species. Infrared spectroscopy allows recording of this fingerprint, and thus identifying the gas species [2]. Furthermore, the gas concentration can be determined by measuring the absorption at the desired wavelengths. High absorption path lengths, and thus large sensor sizes are required to detect small gas concentrations. Therefore, conventional gas spectrometers are often designed as multipass cells, comprising mirrors that guide an infrared light beam multiple times through a fixed volume and onto a detector [2,3]. This multipass cell design is, however, unsuitable for miniaturized gas sensors. There is a need for alternative sensor designs that allow enhance sensitivity on-chip.

Optical materials, such as photonic crystals (PhCs), can be used to trap light efficiently in very small volumes [4]. Here, we employ a microtube PhC as a miniature gas spectrometer. This PhC features a large void space fraction; this allows strong interaction between light and gas molecules in the structure. Slow light effects in the microtube PhC are used to enhance gas absorption, allowing for a small form factor and a high sensitivity.

2. Materials and methods

The PhC structure used in this work consists of an hexagonal lattice of silicon microtubes with a pitch of 6.5 μm, a microtube height of 80 μm, and a microtube wall thickness of 300 nm. The microtube PhCs were fabricated by etching an array of macropores in a Si substrate using a photo-assisted etching technique reported elsewhere [5]. The pitch length is set by a lithographic mask that allows to precisely locate etch pitches at 6.5 μm. The thickness of the tube walls is also controlled by the fabrication process, after etching, a layer of oxynitride allows for a controlled deposition of poly-Si to serve as the microtube walls. The timing of the deposition allows for precise control of the wall thickness leaving precisely controlled microtube geometry. Fig. 1a shows a photograph of a PhC sample; Fig. 1b and c shows scanning electron micrographs of the microtube array and a cross-sectional image of a single microtube used for characterisation.

The microtube PhCs exhibit strong transmittance over a wide spectral range in the MIR at frequencies above the light line [6]. Fig. 2a shows, for example, a transmission spectrum of a microtube PhC with a width of 1.5 mm in the Γ-M transmission direction in a wavelength range above the light line of the PhC. Transmittance of

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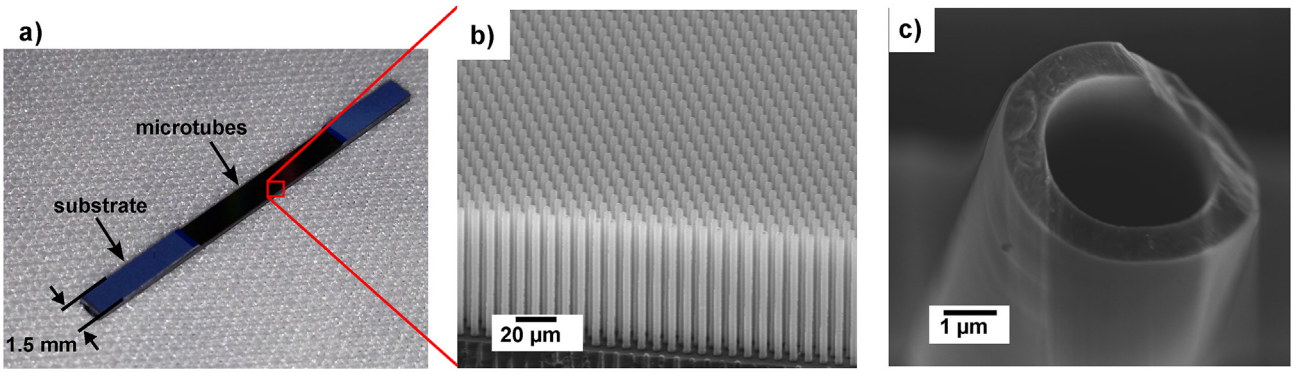

Fig. 1. Geometry of PhC samples and microtube arrays. a) PhC sample with a width of 1.5 mm in transmission direction. The microtube array (black) in the center is located between two stabilizing sections consisting of the Si substrate covered by a Si_3N_4 layer. b) SEM image of an hexagonal microtube array with a lattice pitch of 6.8 µm and a microtube height of 80 µm. c) Cross-sectional view of a microtube with a poly-Si wall thickness of ~600 nm.

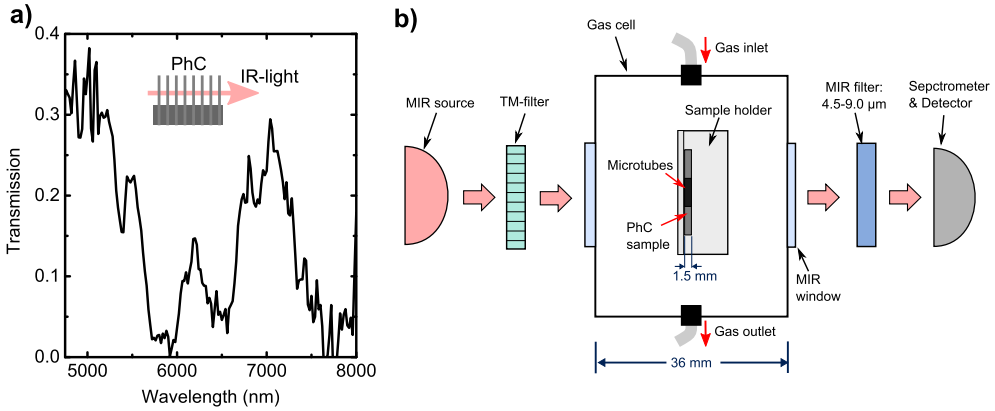

Fig. 2. a) Transmission spectrum of a hexagonal microtube array with a pitch of 6.5 µm in the wavelength range from 5 µm to 8 µm, measured in Γ-M direction. b) Schematic image of the setup for transmission and gas absorption measurements.

up to 35% can be achieved in this wavelength range. This strong transmittance is related to the high aspect-ratio of the microtubes that leads to quasi infinite optical properties in the z-direction, normal to the lattice plane [6]. Radiative losses out of the crystal plane are therefore mostly suppressed, giving the outstandingly high transmittance above the light line.

Fig. 2b shows a schematic of the transmission setup which was used for the gas measurements. The setup comprises a thermal radiator, which generates MIR radiation over a broad spectral range, a grid polarizer to restrict this radiation to TM polarized light, and a custom-built gas cell enclosing the PhC for gas absorption measurements. The gas cell has a housing with MIR transmissive potassium bromide windows on both sides, and is connected to gas tubes for purging the gas cell. The sample is built into a special sample holder in the gas cell, wherein the sample holder is optimized for transmission measurements above the light line of the PhC structure [6]. The setup further comprises a grating spectrometer and a detector to record transmission spectra of the PhC, wherein a bandpass filter, optimized for transmission between 4.5 and 8 µm, is placed in front of the spectrometer to prevent the detection of higher order diffractions.

Propene (C_3H_6) was used for gas absorption measurements as it features several absorption bands throughout the MIR [7]. A propene absorption band between 5.3 and 5.6 µm was investigated in this work. The propene was mixed with gaseous nitrogen (N_2) to set its concentration to 33 vol%. The aim of this paper is to demonstrate slow-light enhanced gas sensing on the corresponding absorption bands of the photonic crystal. The hexagonal lattice pitch of 6.5 µm offers high transmission at the characteristic propene bands of 5.3 and 5.6 µm. Characteristic absorption bands for slow-light in that region are found for 6–7 µm geometries, full characterisation of such bands and geometries is reported elsewhere [6]. To perform reference transmission measurements without gas absorption in the 5.3–5.6 µm region, the gas cell was flushed with pure N_2 which has no absorption bands in this wavelength range [7]. Absorption spectra were derived by dividing transmission spectra recorded with C_3H_6/N_2 mixtures by the transmission spectra recorded from gas cells flushed with N_2 only. Changing the propane concentration would result in a change to the overall transmission shown in Fig. 4a, as in classical spectrometry. In order to observe the effects of slow light from the PhC on the gas sensitivity (Fig. 4c), the signal was normalized the same concentration without PhC.

3. Theory of slow light enhanced gas sensing

The gas sensor that is developed in this work uses slow light to enhance gas absorption in the PhC. Slow light refers to light that propagates with extremely low group velocity v_g [8]. Light propagation through a PhC is governed by its photonic band structure, and the group velocity of a PhC mode corresponds to the slope of the photonic band at the mode frequency ω, and corresponding wave vector k, according to [9]:

$$v_g = \frac{d\omega}{dk} \tag{1}$$